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This Report corresponds practically to the period of the first 8 months of the Project planned to continue for 3 years. Thus some work reported is of initial and preparatory character.

We will present here the aim and the results obtained in each of the three directions of our investigation of the rheologic properties of the solid earth:

1. strain release studies of the circum-Pacific seismic belt;
2. laboratory studies of the behaviour of scale models under stress;
3. development of methods to measure stress and strain variations in the crust, caused by earth's tides and other phenomena.

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1. Strain release studies

a. Aim

Earthquake activity provides important information about the physical conditions in the earth's upper part. It is of interest to carry out investigations for the area with the highest activity - the circum-Pacific belt. Of special interest are aftershock sequences, characterized by an increase of the earthquake activity in a certain region and for a certain time interval. Therefore, our investigation started with strain release studies of the circum-Pacific belt during some aftershock sequences.

For this purpose the method of Benioff was applied, modified to some extent according to the requirements of some new findings.

What we like to know is the dynamics of strain release in earthquake sequences and, later, of a single earthquake, and also the mutual dependence of earthquake activity on adjacent but distinctly separated fault systems.

The stimulus to our investigation was our discovery of an oscillation pattern of the strain release between the two ends of the elongated aftershock area of the Aleutian earthquake of March 9, 1957. It is our current aim to find out, if this result is true also for other aftershock sequences.

b. Results

The increase of strain release at the "ends" of an aftershock area is to be expected theoretically (see E.M. Anderson: The dynamics of faulting, Oliver and Boyd, Edinburgh, London, 1951, 206 pp., and V.I. Keilis-Borok: Some new investigations of earthquake mechanism, Publ. Dom. Obs., Ottawa, Vol. XXIV, No. 10, 1960, pp. 335 - 343). The location of the "ends" of the aftershock area with increased strain release is determined by the direction of the fault zone and

the direction of the stress field. A horizontal compressional field will give rise to ar increase cf stress at the horizontal ends of a dipping fault, having an oblique strike relative to the compressional field, and with a strike slip motion. On the other hand, a compressional field, perpendicular to the strike of a dipping fault will give rise to an increase of stress at the vertical ends (i.e. the upper and lower ends) of the fault surface and to a dip slip motion. For both these extreme cases an oscillation pattern of the strain release has been observed: for the first case for the Aleutian Islands 1957 sequence (see S.J. Duda 1961: Phänomenologische Untersuchung einer Nachbebenserie aus dem Gebiet der Alëuten-Inseln, Zeitschr. Geoph., Vol. 27, Heft 4/5, pp.207 - 213, and S.J. Duda 1962: Phänomenologische Untersuchung einer Nachbebenserie aus dem Gebiet der Alëuten-Inseln, Freiberger Forschungshefte C 132, pp.7 - 90), for the second case - for the Kamchatka 1952 sequence (see R.Z. Tarakanov 1961: The aftershocks tc the earthquake of November 4, 1952, (in Russian), Acad. Sci. USSR (Siberia), Trudy, Fasc. 10, pp. 100-111 and pp. 112-116).

It is obvious, that the real conditions are frequently combinations of the two extreme cases noted above.

As the dominating tectonic movement is strike slip, the oscillation pattern between the horizontal ends of active faults, being the most common, was found in four additional cases, investigated up to now in the Project. These are the Chile 1960 (still under investigation), the Kern County 1952 (on two conjugated faults) and San Francisco 1957 sequences. In one case, the Desert Hot Springs 1948 sequence, no oscillation pattern was found. For details see the paper "Strain release in the circum-Pacific belt: Kern County 1952, Desert Hot Springs 1948 and San Francisco 1957" attached to this Report.

In the attached paper an interpretation is presented of the

tectonical occurrences during the well recorded Kern County 1952 aftershock sequence. This explanation incorporates seismological as well as geodetic and geological published statements. In particular, an interpretation could be given of the dual form of the strain release characteristics, as shown previously by Benioff.

The oscillation pattern is planned to be investigated by periodogram analysis. The observational material must be prepared to an electronic computer treatment. Before that, however, we like to get a better strain conversion equation, giving the dependence of the magnitude of an earthquake upon the strain.

A reliable knowledge of the dependence of the volume of the strained rock upon the magnitude of the corresponding earthquake would mean an improvement of Benioff's method of strain release investigations. In this method, as used hitherto, the volume is assumed constant, independent of magnitude. An investigation was started with the purpose to find an empirical formula giving the magnitude-volume relationship, and consequently a better magnitude-strain dependence. This investigation, to be continued further, gave some qualitative, but not quantitative agreement with theoretical considerations contained in Berckhemer's paper: Die Ausdehnung der Bruchfläche im Erdbebenherd und ihr Einfluss auf das seismische Wellenspektrum, Gerl. Beitr. Geoph., Vol. 71, Heft 1, 1962, pp. 5 - 26.

2. Laboratory investigations

a. Aim

The earth's upper part, where earthquake sequences take place is exposed to a system of stresses and exhibits an internal stress pattern, changing with time. To this body we can apply the methods

of the theory of strength. As in this theory only the simplest cases are given in a mathematical form, other methods for quantitative determinations are used. One of these methods is the photoelastic method, which seems to be very suitable for seismological and generally, tectonophysical considerations. Our aim is to apply this method to stress and strain investigations on scale models under conditions resembling those in nature as much as possible.

b. Results

This phase of our work is still in its planning stage, and no results have so far been obtained. We have looked for a photoelastic instrument by means of which the stress state in a transparent scale model could be established. The scale models shall have characteristic features related in a known manner to the geological bodies.

The first step is to investigate the steady stress state in the scale model, the second - the changes of the stress state with time.

Among a few types we have found an instrument called: Spannungsoptisches Gerät nach Föppl - Hiltscher, made by Ing. D. Tiedemann, München 42, Willibaldstr. 12. This instrument seems to be the best available for our purposes.

We have started a cowork with the photoelastic laboratory of the Royal Water Power Board (Kungl. Vattenfallsstyrelsen), Stockholm, and some test measurements are planned to be carried out there, before we decide to buy an instrument.

3. Field measurements

a. Aim

The empirical description of the rheological behaviour of the earth's crust requires the measurement of a number of parameters. The parameters with the most rapid changes in time, especially in

seismic active areas, are presumably the stress, the strain and the tilt. We will try to install apparatuses for measuring these parameters.

b. Results

The stress state and its changes with time will be measured by means of Prof. N. Hast's sond. After a consultation, the cowork was planned to start in the beginning of 1963.

The strain measurement is planned to be carried out later with a strain seismograph, in case it can be acquired.

The tilts of the earth's surface caused by body tides and air pressure variations are of the order of 0.1" and 0.01" respectively. The Geotechnical Institute in Stockholm was consulted about the preparation of a tiltmeter. The sensitivity of a field tiltmeter developed by the Institute is of the order of 1", but this sensitivity could be increased if the instrument would be adopted as a station instrument.

We have consulted the Swedish Geological Survey in Stockholm about the possibilities to build a seismological station underground in a gallery of a mine, where a set of seismographs, the tiltmeter (after it has been completed) and possibly a strain seismograph could be located. We have got information about the mines, their local conditions and their plans for the future, this information being essential for the planning of an underground seismological station.

Markus Båth

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Project Scientist

A P P E N D I X I

STRAIN RELEASE IN THE CIRCUM-PACIFIC BELT: KERN COUNTY 1952, DESERT HOT SPRINGS 1948, SAN FRANCISCO 1957

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STRAIN RELEASE IN THE CIRCUM-PACIFIC BELT: KERN COUNTY 1952, DESERT HOT SPRINGS 1948, SAN FRANCISCO 1957

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Summary

Three Californian aftershock sequences are investigated with the purpose to check the oscillation pattern of strain release between the two ends of the elongated aftershock zone, as found earlier for the Aleutian Islands 1957 aftershock sequence. In the Kern County 1952 sequence the oscillation pattern was verified not only for the White Wolf fault but also for a second fault, probably the Edison fault, which became active in the sequence. A model is presented, which embodies seismological as well as geological and geodetic statements given by different authors. Possible reasons are discussed for the absence of the oscillation pattern in the Desert Hot Springs 1948 sequence, whereas for the San Francisco 1957 sequence the oscillation pattern could be well asserted. Some inferences are drawn concerning the aftershock appearence in general.

1. INTRODUCTION

Aftershock sequences provide important information about the physical conditions in the earth's upper part, which are responsible for earthquakes. To every earthquake of a given magnitude can be related a certain amount of strain-energy or strain. We follow the suggestion of Benioff to study the strains corresponding to earthquakes.

We consider the part of strain energy, which was converted in the i-th earthquake into seismic energy, to be a function of the geographical coordinates φ, λ, the depth h of the focus and the time of the shock t :

$$\varepsilon_i = \varepsilon_i(\varphi, \lambda, h, t) \qquad (1)$$

If we investigate the strain field in the earth's upper part defined by

$$\varphi_1 \leq \varphi \leq \varphi_2$$

$$\lambda_1 \leq \lambda \leq \lambda_2$$

$$h_1 \leq h \leq h_2$$

in the time interval $t_1 \leq t \leq t_2$,

we can carry out a summation

$$\sum_{i}^{n(\varphi, \lambda, h, t)} \varepsilon_i(\varphi, \lambda, h, t) \qquad (2)$$

where $n(\varphi, \lambda, h, t)$ is the number of earthquakes within the defined volume and time interval. The general expression (2) does not easily lend itself to any immediate practical application.

As the depths h of earthquakes are usually less well known, the strain distribution is determined not for hypocentres but for epicentres, i.e. the depth h is assumed constant, which gives a projection of the real strain distribution on a plane parallel to the earth's surface.

Considering that aftershock areas are usually elongated in one direction (axis), coinciding with the fault zone, we can replace the variables (φ, λ) in (2) by the variables (x, y), where x is the coordinate along the axis and y perpendicular to it. The variable y depends therefore partially upon h - the depth of the earthquake in a fault zone with an oblique dip, y being usually known with a higher accuracy than h.

The formula

$$\sum_{i}^{n(x,\,y,\,t)} \varepsilon_i \,(\, x,\, y,\, h = \text{const} \,,\, t \,) \qquad (3)$$

with

$$x_1 \leq x \leq x_2$$

$$y_1 \leq y \leq y_2$$

$$t_1 \leq t \leq t_2$$

is still too general for practical application.

The following special cases of (3) will be considered:

First case: the summation is carried out for all earthquakes with coordinates x, y up to the time t_2, the end of the investigated time interval. The summation (3) then represents the geographical strain distribution within the given time interval.

Second case: the volume or the area, where the main shock and the aftershocks occurred, is treated as a whole, i.e. in (3) x=const., y=const. (3) then gives the strain release characteristic proposed by Benioff in his theory of aftershock generation.

Third case: x=const.; we consider the time variations of strain release in dependence of y - the width of the aftershock area, being also a measure of the focal depth. This method was applied (not for the strain but for the strain-energy) by Tarakanov (1961) for the Kamchatka 1952 aftershock sequence.

Fourth case: y=const.; we consider the time variations of the strain release along the fault axis. This method has been used by Duda (1962) for the Aleutian 1957 aftershock sequence and will be applied in the following for three Californian aftershock sequences. Thereby we make use of a further feature of aftershock occurrences. It has been observed frequently, that the number of earthquakes and, even more, the corresponding strains are highest near the ends of the fault axis and

smallest in the middle. This is valid for the strike-slip component of the movement on the fault. The total strain released in an aftershock sequence is in this way divided into two parts along the fault axis.

After Benioff we assume the strain ε_i to be proportional to $J_i^{\frac{1}{2}}$, where J_i denotes the seismic energy released in the i-th aftershock. Therefore what will be investigated is the empirical function (3) in the 4th case, where ε_i is replaced by $J_i^{\frac{1}{2}}$, briefly called strain.

2. KERN COUNTY 1952

a. Previous investigations

The Kern County 1952 aftershock sequence has been investigated very thoroughly from many points of view (see Division of Mines, Bulletin 171, 1955). The main shock of July 21, 1952, 11.52.14,4 GMT, and the first affershocks occurred on the White Wolf fault, striking from SW to NE (Figure 1). According to Gutenberg (1955) "the fault plane corresponding to the main shock had at the depth of the source (about 10 miles) a dip of about 60° to 66° towards E 50°S; the slip along the fault at this depth was roughly up towards north in the upper (southeastern) block relative to the lower (northwestern) block; the vertical component of the slip was about 1.4 times the horizontal; the horizontal component corresponded to a relative movement northeastward in the upper block (southeast of the fault), southwestward in the lower block" (northwest of the fault).

Richter (1955) published a table with origin times, epicentres and magnitude for all recorded shocks in Kern County from July 21, 1952 to June 30, 1955. This table can be considered to be complete for shocks with magnitude 4.0 and over. For our investigation only these earthquakes, numbering 222, have been taken into account.

Richter writes about the succession of the aftershocks in time and space, that "for the first 36 hours all located epicentres lie on or south of the White Wolf fault" and "beginning with a large aftershock after $36^h\ 46^m$, aftershocks occur both north and south of the White Wolf fault" and "the mechanical unity of the whole phenomenon is indicated by a tendency for successive shocks to occur in different parts of the active area, rather than repeating from the same point". The last statement will be of special interest for our investigation.

Benioff (1955a) determined a strain characteristic for the White Wolf zone as indicated by the aftershock sequence. He also distinguished between shocks situated SE and NW of the White Wolf faul and drew separate strain release characteristics for the two parts of the after-shock area. Very instructive is the figure 2 in his publication, which shows the projection of all hypocentres on a vertical plane striking NW - SE, i.e. perpendicular to the White Wolf fault line on the surface. As the depths of the foci are not well established, the vertical spread of the hypocentres shows only the repetition of shocks with the same distance from the fault line. There is a sharp decrease of the number of shocks to the northwest of the fault line. There is obviously no continuous passage from the process SE of the White Wolf fault to the process NW of this fault, but instead these are two processes differing at least by the number of shocks.

Another difference was pointed out by Båth and Richter (1958). They investigated the orientation of fault traces and the nature of fault motion for 57 earthquakes of the sequence. They found, that "unlike the main shock, the aftershocks exhibit considerable strike slip with left-hand strike slip dominating on and to the south of White Wolf fault and right-hand strike slip and dip slip to the north of it".

b. Division of the aftershock area into five regions

We divide the aftershocks into those, which occurred SE and NW of the White Wolf fault surface trace in the same manner, as was done by Richter (1955) and Benioff (1955 a) with the exception, that the earthquakes situated NW of the SW end of the fault trace are grouped together with those SE of the White Wolf fault. This is reasonable because they lie clearly on the Pleito fault, which is connected with the White Wolf fault on its SW end (Hill 1955).

It must be noted, that the earthquakes on the Pleito fault could be observed especially in the later stage of the aftershock sequence. This agrees with observations for other aftershock sequences, inasmuch as in course of time an extension of the aftershock area usually occurs, preferably in the direction of the active fault strike.

As there was an accumulation of epicentres to the SE of the White Wolf fault on its SW and NE ends, we have denoted the corresponding regions by I and II (Figure 1). We have excluded some earthquakes in between these regions and called that region V. The reason is, that the strongest earthquakes in V show dip slip movement contrary to the regions I and II.

The earthquakes NW of the White Wolf fault surface trace, and not belonging to the regions I, II and V have been grouped into regions III and IV, based upon their accumulation.

Earthquake sequences usually exhibit an increased activity towards the ends of the fault system, as demonstrated for the sequences in Kamchatka 1952 (Båth & Benioff 1958), Desert Hot Springs 1948 (Richter, Allen & Nordquist 1958), Chile 1960 (St. Amand 1961) and Aleutian Islands 1957 (Duda 1962).

If we except region V, our division is already an indication of the fact, that in the Kern County aftershock sequence not only the

White Wolf fault was active, but also a second fault. This is connected with the former on its NE end and runs roughly to about WNW, i.e. from about Caliente to Bakersfield (see Figure 1 and compare with figure 1 in Hill, 1955).

It seems, that this is the Edison fault which became active in the investigated aftershock sequence, 37 hours later than the White Wolf fault (see plate 1 in Division of Mines, Bull. 171, 1955).

c. Geographical strain distribution

In order to verify this opinion we project the strains corresponding to the particular earthquakes of the aftershock sequence on the assumed fault lines (Figure 2). As expected for a fault with strike slip activity and as shown already by the distribution of epicentres, the strain release is highest on the ends of the White Wolf fault. The strain released increases also in the middle of the active fault, corresponding to the region V with predominating dip slip.

We do not know the exact shape of the second fault assumed to have become active during the investigated sequence. Nevertheless, we project the strains in the regions III and IV on the auxiliary line X', Y', Z, which cannot diverge much from the strike of the second fault. Figure 2 clearly demonstrates the increase of strain release on the ends of the auxiliary line and the gap in between.

We will further show, that the regions I and II on one hand and the regions III and IV on the other are connected dynamically, and that the earthquake activity which began in the regions I, II and V has caused the activity in the regions III and IV.

d. Strain released in the sequence in dependence of time

Figure 3 shows the strain release characteristics for the whole Kern County aftershock area, and separately for the regions I, II, V and III, IV respectively. Benioff (1955 a) published already

strain characteristics for the aftershocks SE and NW of the White Wolf fault. These characteristics differ in some details from ours. The most important difference is that Benioff included some shocks (Nr 117 and 118 from Richter's (1955) table), situated clearly in the SE part of the aftershock area (in our region II) into the strain release characteristic for the NW part of the area. The fact, that they fit well the strain characteristic representing elastic afterworking of a shearing strain does not seem to us to be a sufficient reason.

We have approximated the strain release characteristic for the regions I, II, V by straight lines. Their equations are:

$$\sum_{i}^{n(t)} J_i^{\frac{1}{2}} \begin{cases} = (1.55 + 1.07 \log t).10^{10} \text{ erg}^{\frac{1}{2}} & \text{for } 0.01 \leq t \leq 1.30 \text{ days} \\ = (-9.05 + 4.51 \log t).10^{10} \text{ erg}^{\frac{1}{2}} & \text{for } 1.30 \leq t \leq 4.33 \text{ days} \\ = (1.90 + 1.48 \log t).10^{10} \text{ erg}^{\frac{1}{2}} & \text{for } 4.33 \leq t \leq 908 \text{ days} \end{cases}$$

There is an obvious difference of the strain characteristics of the regions I, II, V and the regions III, IV. According to Benioff's theory of aftershock generation, the former is produced by elastic afterworking resulting from a compressional strain, with a few sudden changes in the intensity of strain release, whereas the latter is produced by elastic afterworking resulting from a shearing strain.

e. Oscillation of strain release

Figure 4 a shows the strain released in the regions I and II in such a way, that above the zero-line are drawn in the logarithmic time scale the strains released in the region I and below - in the region II:

$$\sum_{i}^{n(x,t)} J_i^{\frac{1}{2}} \; (x,\ y = \text{const},\ h = \text{const},\ t).$$

Figure 4 b shows in the same way the strain released in regions III and IV. From this presentation can be seen in which part of the fault a certain strain was actually released. Furthermore, it can be investigated, if there was a statistically random strain release at both ends of the fault or not.

We have divided the time axes in Figure 4 into parts, such that for every part could be established a clear predominance of the strain released in one of the regions. We find an alternative predominance of the strain release in the regions I, II in Figure 4 a and III, IV in Figure 4 b.

For everyone of the time intervals we have plotted the difference of the strains released above and below the zero-lines (crosses in Figure 4). The crosses are placed in the middle of the corresponding time intervals. Therefore, the values of strains expressed by the crosses are more accurate than their times.

Figure 4 a shows a clear oscillation of strain release between the two ends of the White Wolf fault. The period of this oscillation is, generally speaking, increasing with time. If we consider the amplitudes, it seems as if there are present two kinds of oscillation of different intensity and period, the one with large intensity and longer period plotted as a dotted line.

Figure 4 b shows the oscillation of strain release between the two ends of the second fault. The decay of strain released in the successive oscillations is obvious. It is interesting to note, that the oscillation between the regions III and IV stopped 84 days after the main shock and started again 334 days later for a few cycles, simultaneous with increased activity in region I, as shown in Figure 4 a.

If we suppose for the region I, that the different strains released are independent of each other, and suppose the same for the

region II, we can calculate the correlation coefficient between the strains in the two regions. For this purpose we have divided the logarithmic time scale, as in Figure 4 a, into 22 segments, such that $\log t_{i+1} - \log t_i$ is constant, t being the number of days after the main shock and i an integer, $0 < i \leq 22$. The logarithmic time increment then amounts to 0.23. We have computed the correlation coefficient between the strains in regions I and II. A similar calculation was carried out for the regions III and IV. As expected, there is a negative correlation and the coefficient amounts in both cases to about -0.2. The absolute value is low, which is caused especially by the assumption made above, not applicable to aftershock sequences. It must be noted that the value of the correlation coefficients depends both on the time scale selected and on the number of segments used.

The time variation of the oscillation periods is shown in Figure 5, as estimated from the continuous curves in Figure 4, the estimates being uncertain for the highest values of oscillation periods.

An oscillation of strain release could be expected between the deeper and shallower parts of the aftershock volume, as stated by Tarakanov (1961) for the Kamchatka 1952 aftershocks. Unfortunately, the strain in region V, where the dip slip movement is concentrated, is too small for an investigation of the time variation of the release in dependence of depth:

$$\sum_{i}^{n(y,t)} J_i^{\frac{1}{2}}(x = \text{const} , y, h = \text{const} , t)$$

or

$$\sum_{i}^{n(h,t)} J_i^{\frac{1}{2}}(x = \text{const} , y = \text{const} , h, t).$$

f. Discussion

We have found that in an earthquake sequence on a strike slip fault, most strain is released towards both ends of the active fault. There is an oscillation of intensity of strain release between the two ends with increasing period, overlapping the overall decrease of the intensity of strain release.

As their period is increasing, the oscillations cannot be considered as free, but as becoming free: at the beginning of the sequence, when the stress in the earthquake zone is highest, the periods are shortest; with decrease of the stress and release of strain, the periods become longer.

The oscillations of strain release between the ends of a fault system was observed for the Aleutian Islands 1957 aftershock sequence (Duda 1961, 1962). In that case the period of oscillation tended to a value of about 300 days, corresponding to quasi-free oscillations of the fault zone complex. A possible explanation of this phenomenon was also given. In the case of the White Wolf fault the period did not reach the value of 300 days. This means, that the residual stress at the end of the investigated time interval is higher for the White Wolf fault than for the Aleutian Islands, if only the stress state of the fault zone complex is responsible for the oscillation period.

On the other hand, at the second fault in Kern County the oscillation period is higher than at the White Wolf fault at the end of the investigated time interval (Figure 5). This is understandable, because at the beginning, the lateral shear stress was higher at the White Wolf fault, which strikes at an acute angle to the N-S acting force (see below), than at the second fault, where the lateral shear stress was smaller and exceeded the strength of the fault only as a consequence of the action at the White Wolf fault. The oscillation

period is always expected to be shorter in the more stressed material, i.e. in the White Wolf fault, than in the less stressed, i.e. in the second fault.

The Aleutian Islands earthquake sequence seems to be simpler than the Kern County, as in the first one the activity of only one fault system was observed, whereas in Kern County in addition to the White Wolf fault, a second, conjugated one, probably the Edison fault, became active in a later stage of the sequence.

The results of previous and our investigations give the following picture of the occurrences in the Kern County 1952 earthquake sequence.

In the area of the Kern County aftershock sequence a secular compression acts in the N-S direction, producing a crustal shortening (Benioff 1955 b and Hill 1955). This stress produced the main shock of our sequence, with a predominant dip slip component on the White Wolf fault. This movement corresponds to an upthrust of the SE block above the NW, providing a shortening in the N-S direction. This shortening was intensified by the left-hand strike slip component in the main shock and the predominant left-hand movement in the aftershocks on the White Wolf fault (Båth & Richter 1958). The left-hand strike slip is obviously an essential consequence of the fact, that the White Wolf fault has a strike from SW to NE. On the other hand, a fault striking from NW to SE and dipping towards NE will show in the same stress field right-hand strike slip. This is a model for the second fault.

Figure 6 a, b, c shows schematically three situations of the Kern County earthquake zone. Figure 6 a shows the geometrical configuration before the main shock, Figure 6 b - after the main shock and the first aftershocks on the White Wolf fault, Figure 6 c - after the aftershocks on the Edison fault and the remaining aftershocks on the White Wolf fault.

Consequently, what happened in the Kern County earthquake sequence was tectonically nothing but a relative westward movement of the wedge formed by the White Wolf fault and the Edison fault, combined with a downward motion of the wedge relative to the SE block, resulting from the compression in the N-S direction. The westward movement of the wedge and its depression entailed a shortening in the N-S direction and a decrease of the stresses in the area. This picture is very well supported by surveys of triangulation carried out repeatedly by the USCGS in Kern County after the earthquake sequence (Whitten 1955). The results of the triangulation also seem to indicate that the western part of the second fault is convex to the north. This assumption well fits both the fault plane solutions for the region IV (Båth & Richter 1958) and the arrangement of the epicentres in this region (Figure 1 a b). This arrangement has lead to many questionable interpretations of the occurrences to the north of the White Wolf fault.

The strain release on the second fault was a consequence of the redistribution of stresses caused by the main shock and the first aftershocks on the White Wolf fault. On both faults, the strain release exhibited an oscillatory pattern, found already for the Aleutian Islands 1957 aftershock sequence.

From the fault plane solutions of aftershocks (Båth & Richter 1958) can be seen, that a number of earthquakes situated on the White Wolf fault had such a dip slip movement, that the SE block moved down contrary to the main shock. This occurred in the strongest aftershocks with dip slip movement in region V (Figure 2 a). The distinction from the main shock can be easily understood from our model (Figure 6): the upthrust of the SE block in the main shock was reduced because of the left-hand strike slip movement in the aftershocks, which decreased the stresses on the White Wolf fault to the extent, that

it acted for some earthquakes as a normal fault. But for a dip slip component of the movement, the strain should be highest in the middle of the active fault line. This was already reported by Aki (1960) in relation to the Chile 1960 earthquake sequence. He states, that the faulting in the aftershocks near the ends of the zone was predominantly dextral strike slip, and those with vertical movement lay in its central part. For this reason we excluded the region V in Figure 1 from our investigation of the strain release mechanism on the White Wolf fault.

It is more difficult to explain the dip slip earthquakes in the region III (Figures 1 a b) with an upheaval of the southern block, i.e. the cusp of the wedge, as reported by Båth & Richter (1958). Perhaps the very cusp was kept down more than the rest of the wedge in the main shock and in the initial part of the aftershock sequence. Thus an intensive upheaval can be expected on the second fault, dipping to the north, besides its right-hand strike slip, when the wedge moves to the west relative to the surrounding.

The interruption of seismic activity on the second fault for the time between the 84th and 416th day after the main shock (Figure 4 b) can be explained on the base of our model in the following manner. The seismic activity stopped, when the shear stress on the second fault became lower than the strength of the fault against a shearing force. The strength of a fault depends upon the component of the stress, which is perpendicular to the fault plane. If this stress component for any reason decreases, the strength of the fault will also decrease, possibly below the value of the shearing force acting on the fault: seismic activity will start.

In our case the activity continued on the White Wolf fault after it stopped on the second fault 84 days after the main shock. This

continuous activity decreased the stress perpendicular to the second fault, so that on the 418th day the activity started again.

A similar explanation is valid for the increase of the strain release for the regions I, II, V, at 1.30 days after the main shock (Figure 3). At that time, when the activity started on the second fault, the intensity of strain release in the regions I, II, V, increased from $\frac{1.07 \cdot 10^{10}}{t} \cdot \frac{erg^{\frac{1}{2}}}{day}$ to $\frac{4.51 \cdot 10^{10}}{t} \cdot \frac{erg^{\frac{1}{2}}}{day}$. The activity starting on the second fault decreased the stress perpendicular to the White Wolf fault, its strength decreased, and the intensity of strain release could suddenly increase. Of course, the decrease of the intensity at 4.33 days in the regions I, II, V (Figure 3) to the value of $\frac{1.48 \cdot 10^{10}}{t} \cdot \frac{erg^{\frac{1}{2}}}{day}$ cannot be simply explained.

From our model for the Kern County aftershock sequence it is obvious, that on the White Wolf fault a dip slip upthrust of the SE block and a left-hand strike slip has taken place as a yielding from the compression in the N-S direction. Really it was stated by Benioff (1955 a), that the strain characteristic for earthquakes on the White Wolf fault has the form as resulting from a compressional strain of the rock in the strain zone.

On the second fault the yielding occurred only as a right-hand strike slip movement: the N-S compression caused indirectly a shearing force on it exceeding its strength which had been decreased by the activity on the White Wolf fault. It was also stated by Benioff (1955 a), that the strain characteristic for the earthquakes to the north of the White Wolf fault, on our second fault, has the form as resulting from a shearing strain.

There was a distinct time difference between the beginning of the aftershocks on the White Wolf fault and on the second fault. This is

an evidence in favour of the opinion that the activity on the second fault was caused by the activity on the White Wolf fault. It seems as if the Kern County aftershock sequence was a clear instance of a mechanical interrelationship between two different faults.

We conclude

1) that the implicit supposition usually made in investigations of earthquake sequences, that such sequences in a certain area and a certain time interval are independent of the earthquakes in another area, nearby but perhaps also remote, in the same time interval, has only a limited value and

2) that it is more probable that an aftershock sequence is independent of outside influences in its earlier stage of the duration of hours or days after the main shock, than in the later stage reaching hundreds and even thousands of days.

3. DESERT HOT SPRINGS 1948

The aftershock sequence of the earthquake on December 4, 1948, with magnitude 6½, in southern California at 33.9° N, 116.3° W was investigated by Richter, Allen & Nordquist (1958). They have given the geographical distribution of strain released in all recorded aftershocks down to magnitude 3, up to January, 1957 (figure 6 in the publication quoted). This distribution shows clearly that there were two centres of increased strain release situated at the ends of the aftershock area. This area was elongated parallel to the surface trace of the Mission Creek fault, striking from NW to SE.

No fault plane solutions are known for the aftershocks, but the geographical distribution of strain release points to a considerable amount of strike slip movement in the aftershocks.

Figure 7 shows in the logarithmic time scale the strains released in the regions I (SE centre) and II (NW centre). The main

shock occurred in I. No simple time division seems to be possible for this aftershock sequence, in other words no obvious oscillation pattern exists. Instead the strain release increased and decreased almost simultaneously in the regions I and II, at least part of the time investigated. The correlation coefficient between the strain release in the two regions amounts to +0.02 ,i.e. practically no correlation at all.

It is difficult to know the reason for the lack of the oscillation pattern in this sequence, before more cases are investigated. Among possible factors we would like to mention two:

1) The total strains released in the regions I and II are nearly equal for the Desert Hot Springs sequence, as found by Richter, Allen & Nordquist (1958). In all other investigated sequences with an oscillation pattern, there was a clear asymmetry between strains released in the two regions.

2) Richter, Allen & Nordquist (1958) use for the calculation of the volume of the strained rock "a 35 km depth and an area outlined by the zone of aftershock activity", with a length of 18 km. Thus, the volume has a depth almost twice its length, which has never been the case for an aftershock sequence with oscillation pattern , investigated hitnerto. In these cases, the length was usually from a few times up to more than ten times the depth.

4. SAN FRANCISCO 1957

On March 22, 1957, 19.44.21 GMT, an earthquake of magnitude 5.3 occurred in California at 37°40' N, 122° 29' W . It was followed by an aftershock sequence, investigated by Tocher (1959). He published a table with all aftershocks down to magnitude 3 for the time up to June 13, 1957. These data were used for a study of the distribution

of strain release in space and time, in the same manner as above.

The distribution of the epicentres (figure 2 in Tocher's paper) shows, that the aftershocks lie in an area elongated in the direction of the San Andreas fault trace, striking about N 35-38° W. The fault has a dip of about 78° in the NE direction.

The location of a single epicentre has an uncertainty not exceeding about 2 km. The depth of the shocks ranges from about 4 to 11 km and could be determined for the deeper shocks with the same accuracy as the epicentres, while the uncertainity is somewhat greater for the shallower shocks.

We have divided the aftershock area into 16 segments perpendicular to the direction of strike, each with a length of about 1 km. Figure 8 shows the strain distribution in the segments for the time interval March 22, 1952 - June 13, 1957 for all reported aftershocks. It can be seen, that the strain release increases towards the ends of the aftershock area, as observed for all investigated sequences. The question arises which segment should be considered to divide the aftershock area into two regions. Between the segments 8 and 12 there is an increase of strain release, resembling the picture for the White Wolf fault (Figure 2 a). Unfortunately, no fault plane solutions are known for the aftershocks. Only for the main shock Tocher suggests, that there was a "movement on a steeply dipping thrust fault, with the continental side rising with respect to the oceanic side. The strike slip component of the movement, if any, was at most only about half the dip slip component". The epicentre of the main shock is situated in segment 12, near the middle of the aftershock zone, where the vertical movement is expected to be the highest (compare Aki 1960 and above).

Based on the findings of fault plane solutions and strain distri-

butions for the White Wolf fault we consider the segments 9, 10, 11 to correspond primarily to dip slip movement, and the segments from 1 to 8 and from 12 to 16 primarily to strike slip movement.

Just as for the region V on the White Wolf fault, the strain release in the segments 9, 10, 11 is too small for an investigation of possible oscillations of its intensity between deeper and shallower parts of the aftershock zone.

On the other hand, we have constructed the function:

$$\sum_{i}^{n(x,\,t)} J_i^{\frac{1}{2}}(x,\ y = \text{const},\ h = \text{const},\ t)$$

giving the succession in time of strain release in the regions I and II defined in the manner shown in Figure 8, and supposed to be formed primarily by a dextral strike slip. In Figure 9 we find a clear shift of strain release between the two regions for about two oscillation periods.

The small value of the oscillation periods, the biggest being of the order of two days, would mean a high state of stress present in the fault zone. If this is true, we conclude that a relatively small earthquake with a poor aftershock sequence does not necessarily mean, that no further stresses are present in the fault zone. The stresses may only be prevented from release because of the strength of the material, even after a partial release has taken place.

The correlation coefficient between strain release in regions I and II amounts to -0.3.

It is surprising, that the aftershocks started in region II, whereas the main shock occurred in region I. Usually the aftershocks start at that end of the aftershock area, where the main shock occurred. The exception in the case of the San Francisco sequence is perhaps caused

by the fact, that - as Tocher writes - at least two additional after-shocks of magnitude above 3 occurred during the interval of 8 minutes after the main shock, before the activity started in region II (Figure 9). It seems probable, that these two shocks, which could not be listed because of the strong noise on seismograms caused by the main shock, occurred in region I, near the epicentre of the main shock.

5. ACKNOWLEDGMENT

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1962 December.

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(Legends for figures)

FIG. 1. - Geographical distribution of epicentres in the Kern County 1952 aftershock sequence: a) July 21-31, 1952; b) Aug. 1, 1952-May 28, 1955. Solid lines indicate fault zones and dashed lines limits between regions I-V.

FIG. 2. - Strain release distribution along fault lines: a) regions I, II and V (White Wolf fault); b) regions III and IV (second fault).

FIG. 3. - Strain release characteristics for the whole Kern County aftershock area and separately for the regions I, II, V and III, IV. Width of each segment is 7.5 km.

FIG. 4. - Oscillation patterns of strain release in the Kern County aftershock sequence: a) regions I and II; b) regions III and IV.

FIG. 5. - Strain oscillation periods in dependence of time (Kern County).

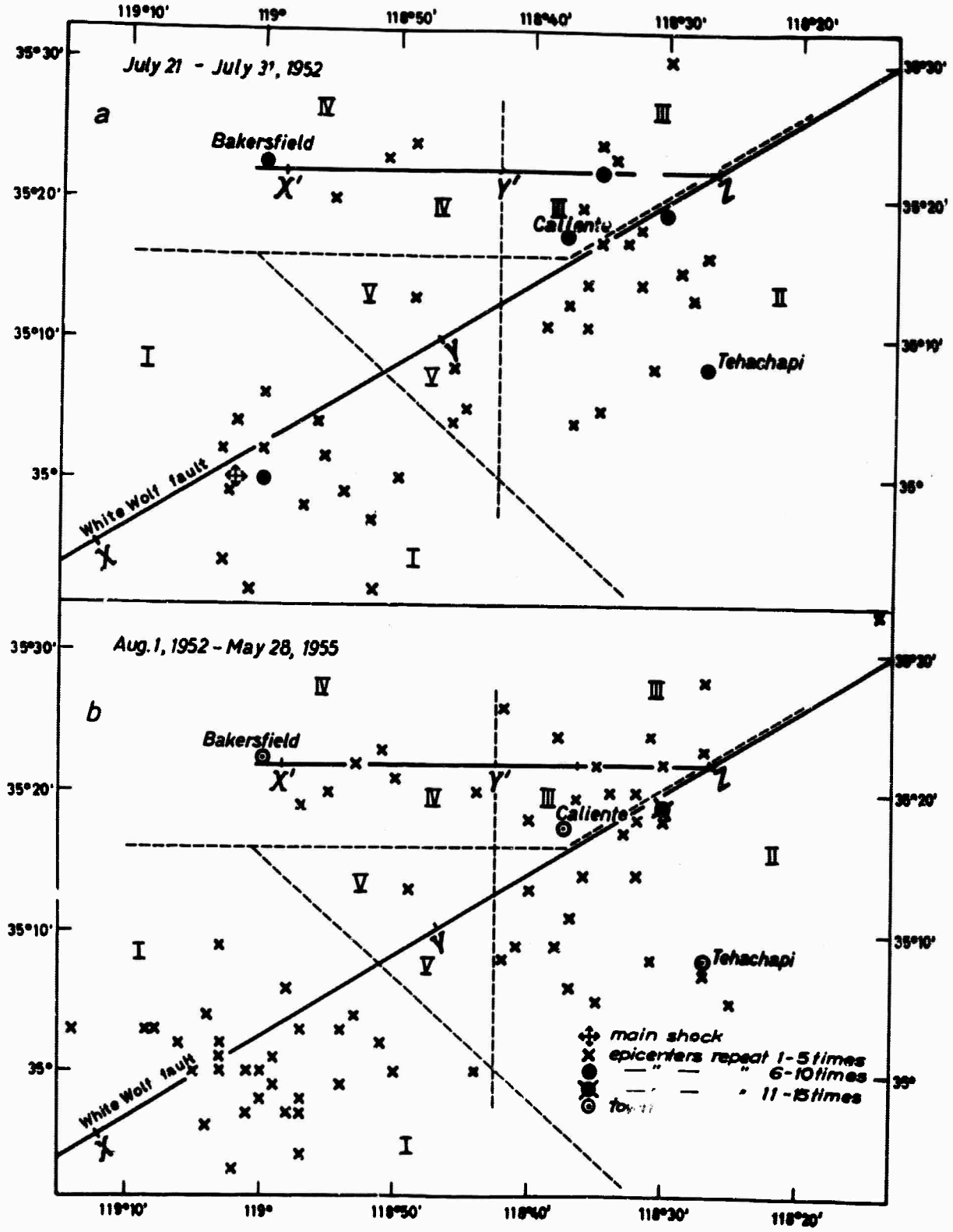
FIG. 6. - Three successive stages (a,b,c) in the dynamical development in the Kern County aftershock sequence. Left-hand drawings give a three-dimensional picture, and the right-hand the corresponding two-dimensional, as seen from above. Heavy arrows indicate stress, gradually reduced in the sequence.

FIG. 7. - Strain release in Desert Hot Springs 1948 aftershock sequence in region I (SE end of fault) and region II (NW end of fault).

FIG. 8. - Strain release distribution along the fault for the San Francisco 1957 sequence. Width of each segment is 1 km.

FIG. 9. - Oscillation pattern of strain release in the San Francisco aftershock sequence.

FIG. 1


119°10'
119°
118°50'
118°40'
118°30'
118°20'
35°30'
35°20'
35°10'
35°
July 21 - July 31, 1952
a
Bakersfield
Caliente
Tehachapi
White Wolf fault
X
X'
Y
Y'
Z
Aug. 1, 1952 - May 28, 1955
b
main shock
epicenters repeat 1-5 times
" " 6-10 times
" " 11-15 times

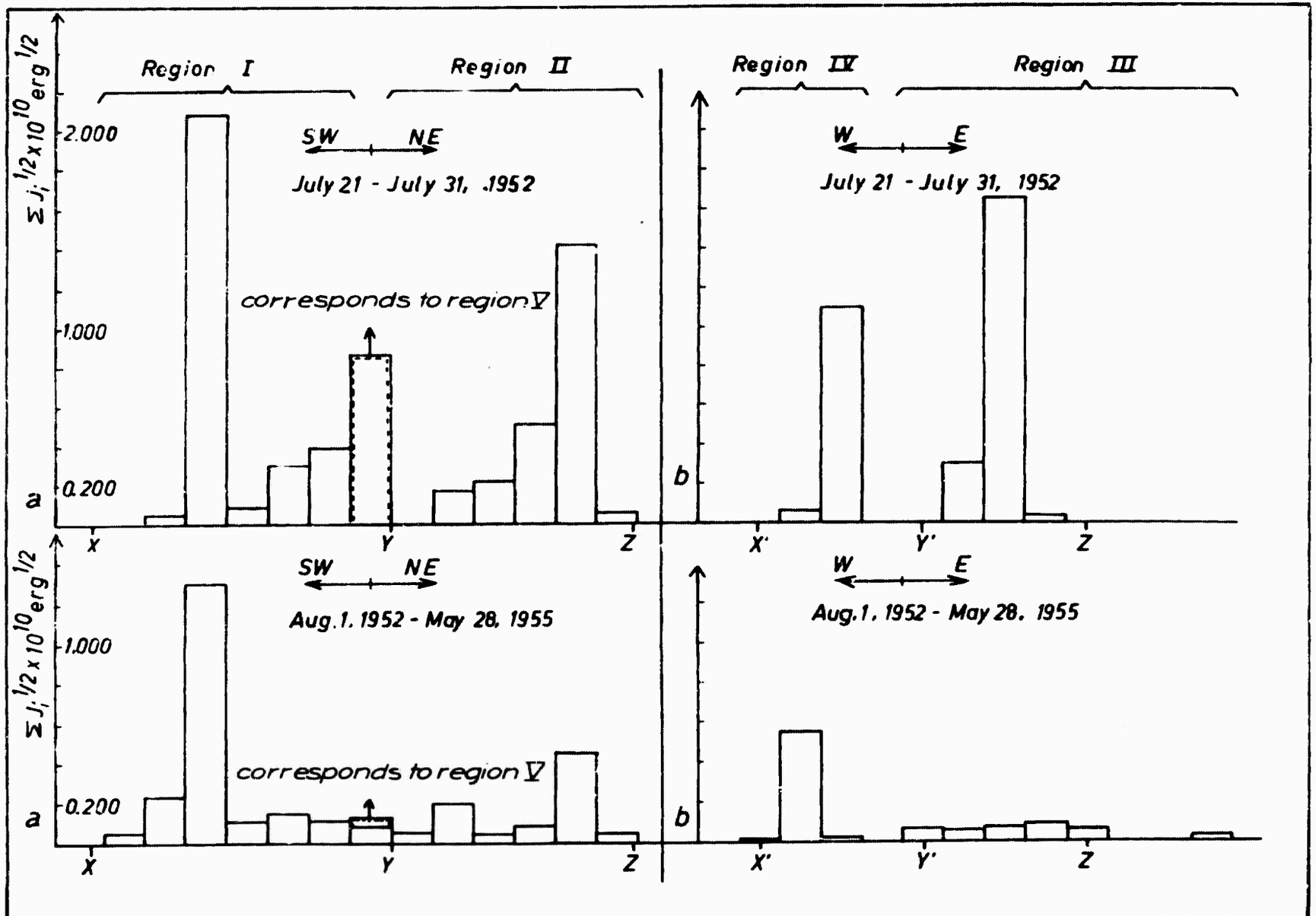

Region I
Region II
Region IV
Region III
SW
NE
W
E
July 21 - July 31, 1952
Aug. 1, 1952 - May 28, 1955
corresponds to region V
$\Sigma J_i^{1/2} \times 10^{10}$ erg $^{1/2}$
2.000
1.000
0.200
a
b
X
Y
Z
X'
Y'
Z'

FIG. 2

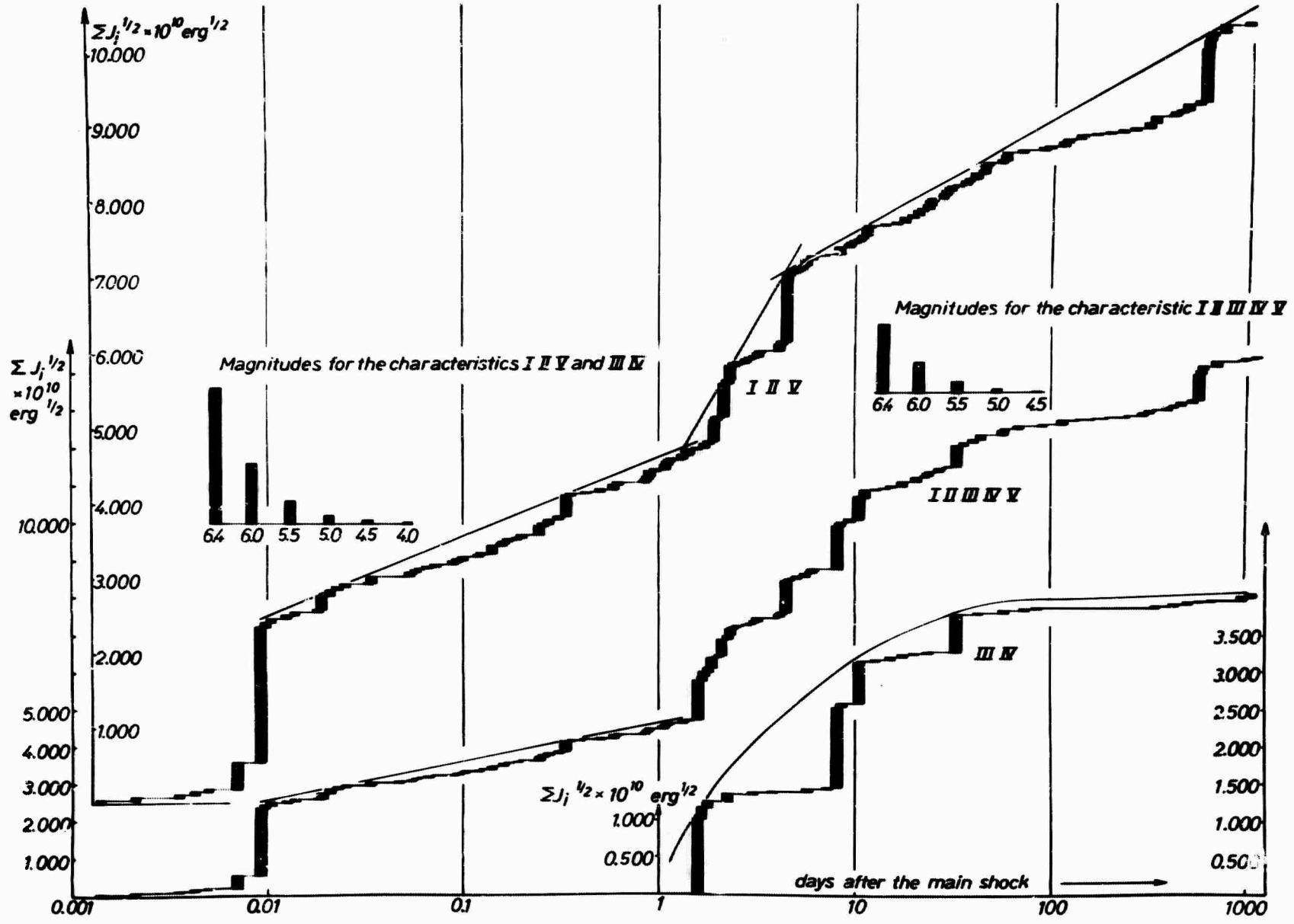

$\Sigma J_i^{1/2} \times 10^{10}$ erg$^{1/2}$
10.000
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
Magnitudes for the characteristics I II V and III IV
6.4 6.0 5.5 5.0 4.5 4.0
I II V
Magnitudes for the characteristic I II III IV V
6.4 6.0 5.5 5.0 4.5
I II III IV V
III IV
$\Sigma J_i^{1/2} \times 10^{10}$ erg$^{1/2}$
10.000
5.000
4.000
3.000
2.000
1.000
1.000
0.500
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.001
0.01
0.1
1
10
100
1000
days after the main shock

FIG. 3

FIG.4

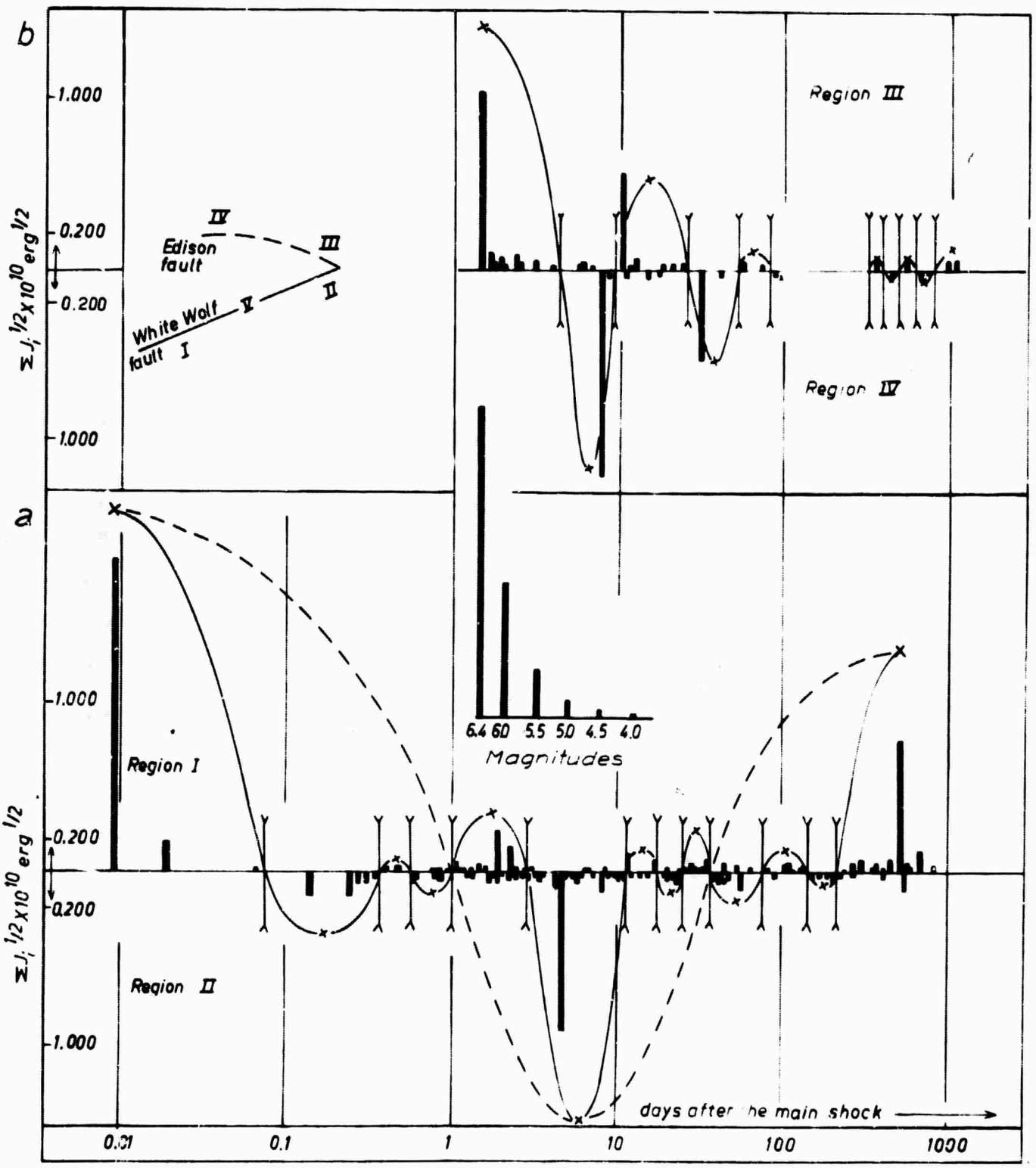

b
1.000
0.200
0.200
1.000
$\Sigma J_i^{1/2} \times 10^{10}$ erg $^{1/2}$
IV
Edison fault
III
White Wolf fault I
II
Region III
Region IV
a
1.000
0.200
0.200
1.000
$\Sigma J_i^{1/2} \times 10^{10}$ erg $^{1/2}$
Region I
Region II
6.4 6.0 5.5 5.0 4.5 4.0
Magnitudes
days after the main shock
0.01
0.1
1
10
100
1000

FIG.5

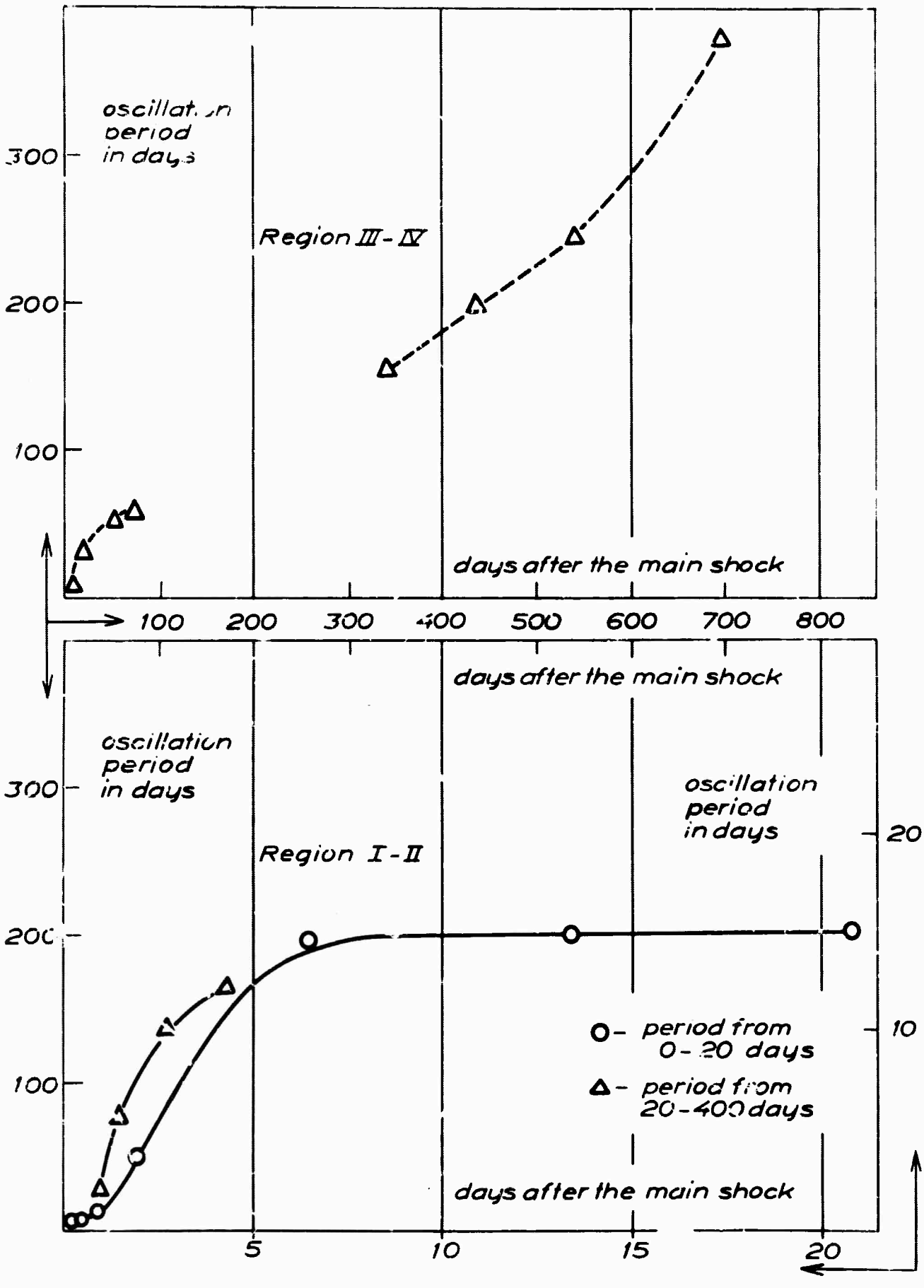
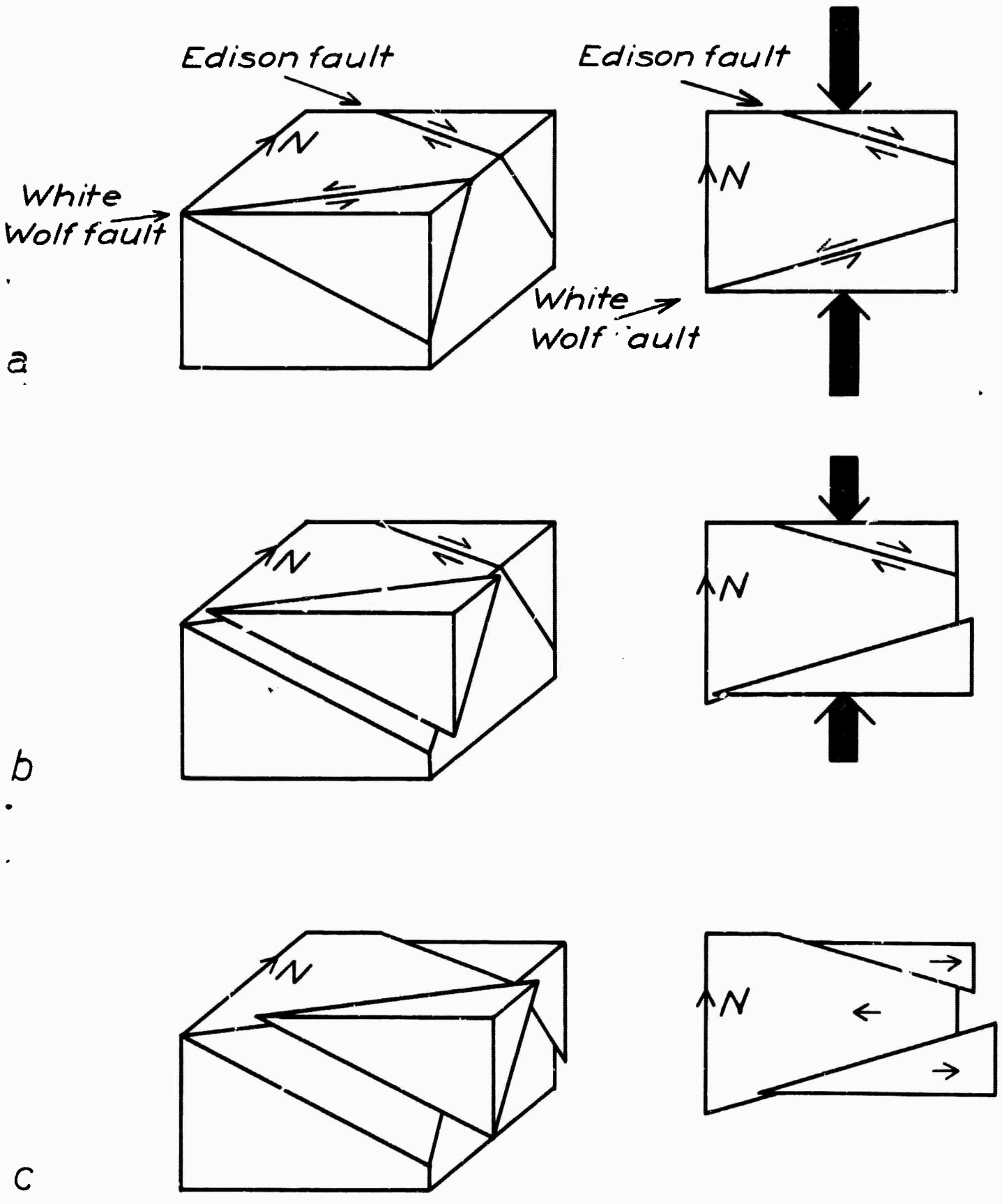

oscillation period in days
300
200
100
Region III - IV
days after the main shock
100
200
300
400
500
600
700
800
days after the main shock
oscillation period in days
300
200
100
Region I - II
oscillation period in days
20
10
O - period from 0 - 20 days
Δ - period from 20 - 400 days
days after the main shock
5
10
15
20

FIG.6


Edison fault
White
Wolf fault
N
a
Edison fault
White
Wolf fault
N
b
N
N
c
N
N

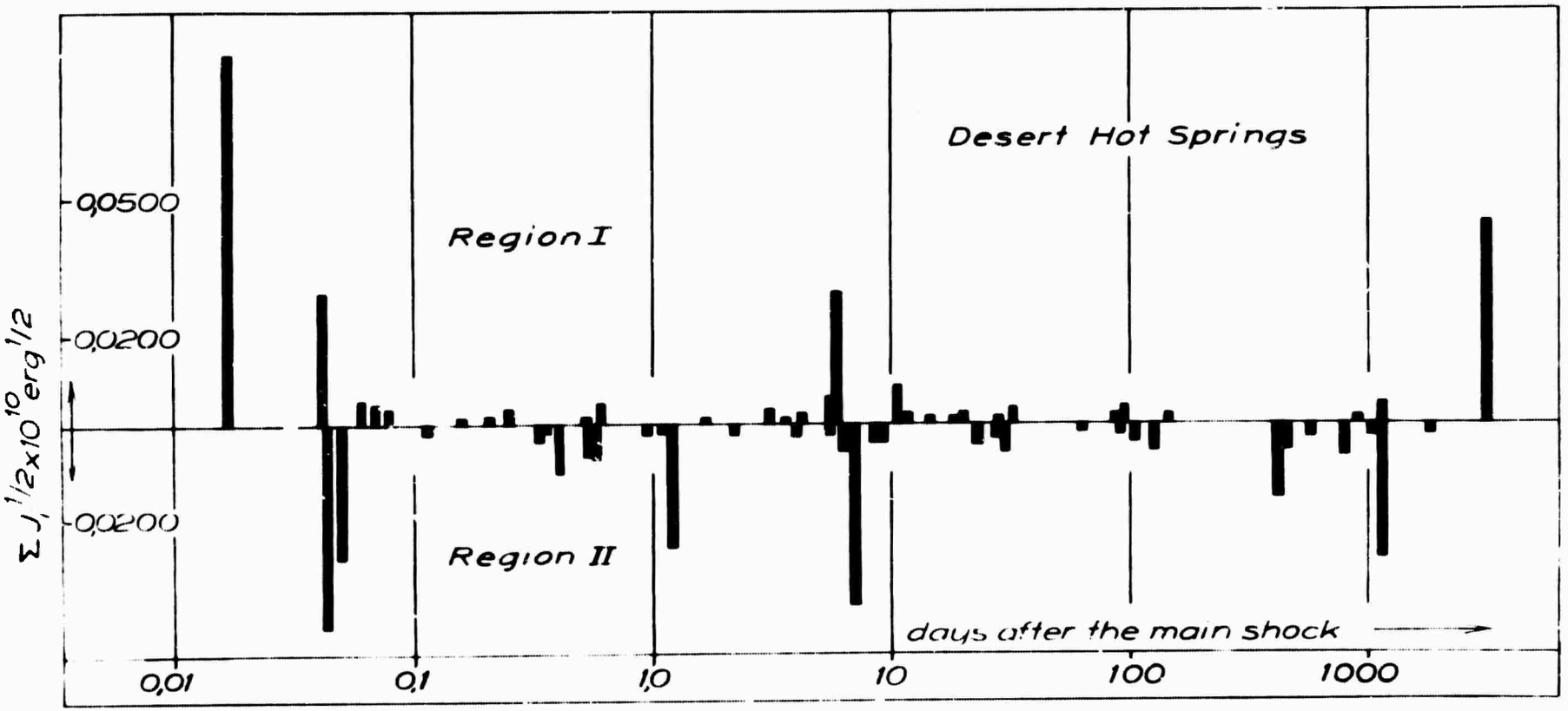

Desert Hot Springs
Region I
Region II
0,0500
0,0200
0,0200
$\Sigma J_i^{1/2} \times 10^{10}$ erg $^{1/2}$
days after the main shock
0,01
0,1
1,0
10
100
1000

FIG.7

FIG.8

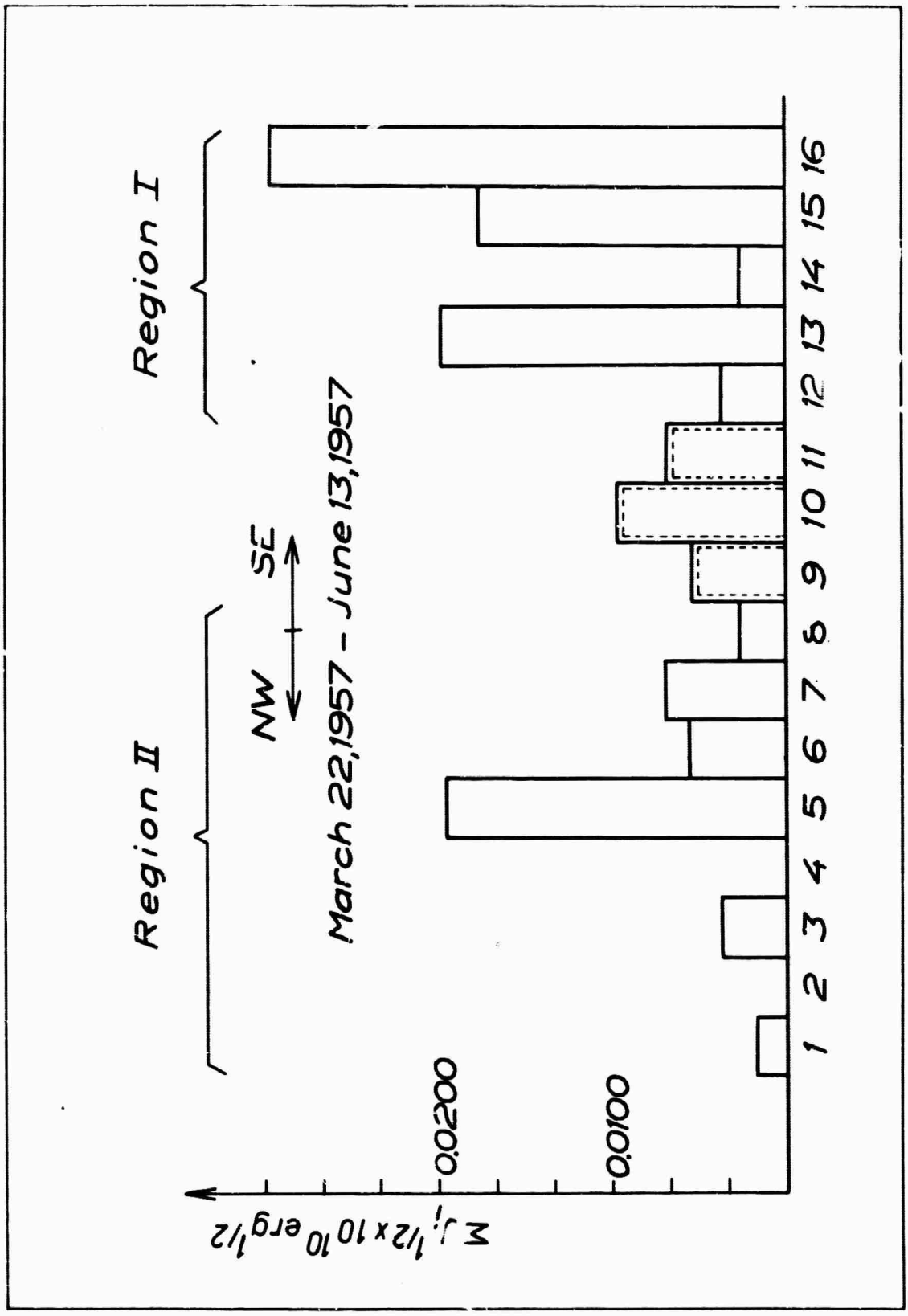
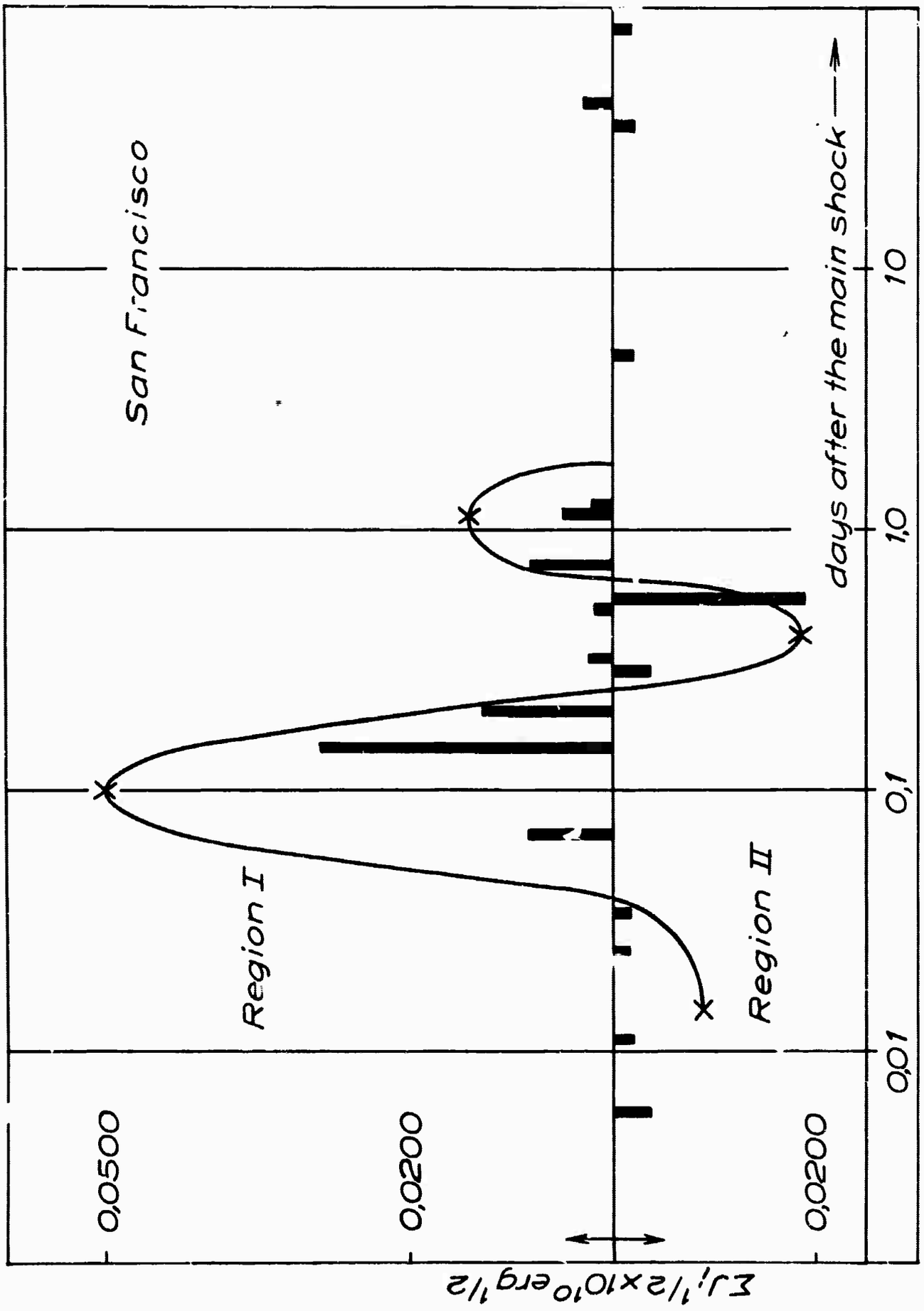

Region I
Region II
NW
SE
March 22,1957 - June 13,1957
0.0200
0.0100
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

FIG.9


San Francisco
Region I
Region II
days after the main shock
0,01
0,1
1,0
10
0,0500
0,0200
0,0200
$E_i^{1/2} \times 10^{10}$ erg$^{1/2}$